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Search for heavy stable charged particles in pp collisions at $\sqrt{s} = 7\,\text{TeV}$

The CMS collaboration

Abstract: The result of a search at the LHC for heavy stable charged particles produced in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ is described. The data sample was collected with the CMS detector and corresponds to an integrated luminosity of 3.1 pb^{-1}. Momentum and ionization-energy-loss measurements in the inner tracker detector are used to identify tracks compatible with heavy slow-moving particles. Additionally, tracks passing muon identification requirements are also analyzed for the same signature. In each case, no candidate passes the selection, with an expected background of less than 0.1 events. A lower limit at the 95% confidence level on the mass of a stable gluino is set at $398\,\text{GeV}/c^2$, using a conventional model of nuclear interactions that allows charged hadrons containing this particle to reach the muon detectors. A lower limit of $311\,\text{GeV}/c^2$ is also set for a stable gluino in a conservative scenario of complete charge suppression, where any hadron containing this particle becomes neutral before reaching the muon detectors.

Keywords: Hadron-Hadron Scattering

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Contents

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1 Introduction

Heavy stable (or quasi-stable) charged particles (HSCPs) appear in various extensions of the standard model (SM) [1–8]. If the lifetime of an HSCP produced at the Large Hadron Collider (LHC) is longer than a few nanoseconds, the particle will travel over distances that are comparable or larger than the size of a typical particle detector. In addition, if the HSCP mass is $\gtrsim 100\,\mathrm{GeV}/c^2$, a significant fraction of these particles will have a velocity, $\beta \equiv v/c$, smaller than 0.9. These HSCPs will be directly observable through the distinctive signature of a high momentum (p) particle with an anomalously large rate of energy loss through ionization (dE/dx).

Previous collider searches for HSCPs have often been performed under the assumption that these particles lose energy primarily through low-momentum-transfer interactions, even if they are strongly interacting, and are therefore likely to reach the outer muon systems of the detectors and be identified as muons [9–13]. The interactions with matter experienced by a strongly-interacting HSCP, which is expected to form a bound state (R-hadron) [14] in the process of hadronization, can lead to it flipping the sign of its electric charge or becoming neutral. A recent study [15] on the modeling of nuclear interactions of HSCPs traveling through matter, favours a scenario of charge suppression. In this model the majority of R-hadrons containing a gluino, $\widetilde{\mathrm{g}}$ (the supersymmetric partner of the gluon), or a supersymmetric bottom squark, are expected to emerge as neutral particles after traversing an amount of material typical of the detectors operating at LEP, the Tevatron, or LHC. If this model is correct, the majority of these HSCPs would not be observed in the muon system of a typical collider detector. Experimental strategies that do not rely on the muon-like behavior for the HSCPs are therefore of great importance. For instance, searches have been performed for very slow ($\beta \lesssim 0.4$) R-hadrons containing a gluino brought to rest in the detector [16, 17].

In this article we present a search for HSCPs produced in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ at the LHC with the Compact Muon Solenoid (CMS) detector [18]. The search is based on the data sample collected between April and August 2010 corresponding to an integrated luminosity of 3.1 pb^{-1}. We use triggers requiring: a high-transverse-momentum muon ($p_T > 9\,\mathrm{GeV}/c$); or a dimuon pair ($p_T > 3\,\mathrm{GeV}/c$ for each muon); or calorimeter-based missing transverse energy ($E_\mathrm{T}^\mathrm{miss} > 100\,\mathrm{GeV}$), to search for HSCPs failing muon identification or emerging mainly as neutral particles after traversing the calorimeters; or a high-transverse-energy jet ($E_T > 100\,\mathrm{GeV}$) to search for HSCPs accompanied by substantial hadronic activity. The analysis makes use of two approaches. In a first selection, referred to as "*tracker-only*", the HSCP candidates are searched for as individual tracks reconstructed in the inner tracker detector with large dE/dx and p_T. A second selection, referred to as "*tracker-plus-muon*", additionally requires that the track is identified as a muon in the outer muon detector. For both selections, the mass of the candidate is calculated from the measured p and dE/dx.

2 The CMS detector

The central feature of the CMS detector is a 3.8 T superconducting solenoid of 6 m internal diameter surrounding a silicon pixel and strip tracker, a crystal electromagnetic calorimeter, and a brass-scintillator hadronic calorimeter. Muons are measured in gaseous detectors embedded in the iron return yoke. Centrally produced charged particles are measured in the tracker by three layers of silicon pixel detectors, followed by ten microstrip layers. At pseudorapidities ($\eta \equiv -\ln\tan(\theta/2)$, where θ is the polar angle measured with respect to the beam direction) above ≈ 1.5, particles are tracked in two pixel and twelve strip layers arranged in disks perpendicular to the beam axis. In this analysis, the dE/dx measurement is based only on the information from the silicon strip detectors. The dE/dx measurement precision is limited by the silicon strip analogue-to-digital converter (ADC) modules that are characterized by a maximum number of counts per channel corresponding to about three times the average charge released by a minimum-ionizing particle (MIP) in 300 μm of silicon. This is the thickness of the modules mounted in the innermost silicon strip central layers. The p_T resolution for tracks measured in the central (forward) region of the silicon tracker is 1% (2%) for p_T values up to $50\,\mathrm{GeV}/c$ and degrades to 10% (20%) at p_T values of $1\,\mathrm{TeV}/c$. The trigger and reconstruction efficiencies for HSCPs in the muon detectors are limited by the requirements on the arrival time of the particles at the muon system. These requirements affect the efficiency for detecting slow HSCPs. The dependence of the muon trigger efficiency on the particle velocity is studied using data and Monte Carlo (MC) simulations and found to decrease, below $\beta = 0.7$. The muon trigger becomes completely inefficient at $\beta = 0.5$. A much more detailed description of the CMS apparatus can be found elsewhere [18].

3 Candidate selection and background estimation

Candidate HSCPs are pre-selected by requiring a track with $|\eta| < 2.5$, $p_T > 15\,\mathrm{GeV}/c$, relative uncertainty on the p_T less than 15%, and transverse (longitudinal) impact parameter with respect to the reconstructed primary collision vertex less than 0.25 (2.0) cm. Candidate tracks are also required to have at least three measurements in the silicon-strip detector. For the tracker-plus-muon selection, we additionally require the track to be compatible with track segments reconstructed in the muon system. As an estimator of the degree of compatibility of the observed charge measurements with the MIP hypothesis, a modified version of the Smirnov-Cramer-von Mises [19, 20] discriminant is used:

$$I_{as} = \frac{3}{N} \times \left(\frac{1}{12N} + \sum_{i=1}^{N} \left[P_i \times \left(P_i - \frac{2i-1}{2N} \right)^2 \right] \right), \tag{3.1}$$

where N is the number of charge measurements in the silicon-strip detectors, P_i is the probability for a MIP to produce a charge smaller or equal to the i-th charge measurement for the observed path length in the detector, and the sum is over the track measurements ordered in terms of increasing P_i. Non-relativistic HSCP candidates will have the value of the discriminant I_{as} approaching unity. The modification applied to the original form of the discriminant consists of multiplicating by P_i the term in round brackets. In this way the I_{as} value for tracks reconstructed with an anomalously low dE/dx, which may result from rare accidental associations of noise signals, is pushed toward low values. Thus the modification eliminates the sensitivity of the original discriminant to incompatibility with the MIP hypothesis due to low ionization. The charge probability density function used to calculate P_i is obtained using tracks with $p > 5\,\mathrm{GeV}/c$ in events collected with a minimum bias trigger. Figure 1 shows normalized distributions of p_{T} and I_{as} in data and two MC samples, for candidates passing the tracker-only pre-selection. The first MC sample contains events from QCD processes. The second MC sample contains signal events from pair-production of stable $\widetilde{\mathrm{g}}$ with a mass of $200\,\mathrm{GeV}/c^2$. Both samples are generated with the PYTHIA v6.422 [21] MC package. More details on the simulation of the signal sample will be given below. The MC QCD simulations are found to reproduce the data, and the simulated signal is clearly separated. Because of the limited number of available simulated events with low transverse-momentum transfers, the MC QCD distributions display bin-to-bin variations in the size of the statistical errors.

The most probable value of the particle dE/dx is determined using a harmonic estimator I_h of grade $k = -2$:

$$I_h = \left(\frac{1}{N} \sum_i c_i^k \right)^{1/k}, \tag{3.2}$$

where c_i is the charge per unit path length in the detector of the i-th measurement for a given track. In order to estimate the mass (m) of highly ionizing particles, the following relationship between I_h, p, and m is assumed:

$$I_h = K \frac{m^2}{p^2} + C. \tag{3.3}$$

Equation 3.3 reproduces the Bethe-Bloch formula [22] with an accuracy of better than 1% in the range $0.4 < \beta < 0.9$, which corresponds to $1.1 < (dE/dx)/(dE/dx)_{MIP} < 4.0$.

JHEP03(2011)024

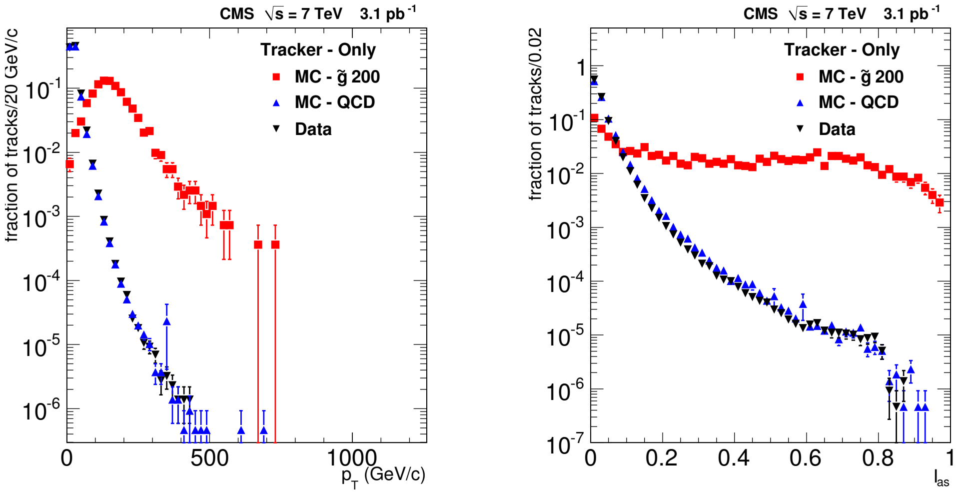

Figure 1. Normalized distributions of p_T (left) and I_{as} (right) in data and two MC samples, for candidates passing the tracker-only pre-selection. The two MC samples contain events from QCD processes and from pair-production of $\tilde{\mathrm{g}}$ with a mass of 200 GeV/c^2, respectively.

The empirical parameters K and C are determined from data using a sample of low-momentum protons, for which the fitted values are $K = 2.579 \pm 0.001\,\mathrm{MeV\ cm^{-1}}\ c^2$ and $C = 2.557 \pm 0.001\,\mathrm{MeV\ cm^{-1}}$, and the mass resolution is 7%. The reconstructed mass distribution for kaons and protons is in very good agreement with the one obtained from MC following this procedure [23]. For masses above 100 GeV/c^2, the mass resolution is expected to worsen because of the deterioration of the momentum resolution and because of the limit on the maximum charge that can be measured by the silicon strip tracker ADCs, which also affects the mass scale. These effects are taken into account by the MC: for a 300 GeV/c^2 HSCP, the mass resolution and the reconstructed peak position are found to be 12% and 265 GeV/c^2, respectively.

The search is performed as a counting experiment. Signal candidates are required to have I_{as} and p_T greater than threshold values and the mass to be in the range of 75 to 2000 GeV/c^2, allowing sensitivity to HSCP masses as low as 100 GeV/c^2. The I_{as} distribution for the pre-selected tracks, and in particular its tail, depends strongly on the number of charge measurements on the track. Thus, to increase the sensitivity of the search, pre-selected tracks are divided into subsamples according to the number of silicon strip measurements. Tracks with 18 measurements or more are merged into a single subsample. Tracks with a number of measurements in the range of 3 to 8 are also merged into a single subsample. In total 11 subsamples are formed whose populations do not differ by more than a factor of five. The I_{as} (p_T) threshold in each subsample is determined by requiring a constant efficiency on data for all subsamples, when the threshold is applied separately. A method that exploits the absence of correlation between the p_T and dE/dx measurements in data is used to estimate the background from MIPs. In a given subsample j, the number of tracks that are expected to pass both the final p_T and I_{as} thresholds set for the subsample is estimated as $D_j = B_j C_j / A_j$, where A_j is the number of tracks that fail both the I_{as} and p_T selections and B_j (C_j) is the number of tracks that pass only the I_{as} (p_T) selection. The B_j and C_j tracks are then used to form a binned probability density function in I_h (p) for the D_j tracks. Finally, using the mass determination (eq. 3.3), the full mass spectrum of the background in the signal region D is predicted.

By comparing the predicted and observed number of tracks for several very loose selections in a control region of the mass spectrum, corresponding to masses below 75 GeV/c^2, the prediction is found to underestimate systematically the observation by 12% (5%) for the tracker-only (tracker-plus-muon) selection. After correcting the predicted background by this amount, the remaining background systematic uncertainty is conservatively estimated as twice the r.m.s. of the prediction-to-observation ratio distribution The resulting uncertainty on the predicted background is 14% (17%).

As significant background rejection can be obtained without a sizable effect on the signal efficiency, the final selection is optimized by requiring the total expected background in the search region to be ~ 0.05 events. This low-background choice optimizes the discovery potential even if just a handful of events are observed, and at the same time maintains significant exclusion sensitivity in the case that no events are observed.

4 Results

In addition to the final "*tight*" selection, the result of a "*loose*" selection is reported in table 1. The loose selection retains a relatively large number of background candidates and allows us to compare the background prediction with the observed data. Figure 2 shows good agreement between the observed and predicted mass spectrum obtained using the loose selection for the tracker-plus-muon and tracker-only candidates.

The results of the search with the final selection are also presented in table 1. No candidate HSCP track is observed in either the tracker-only or tracker-plus-muon analysis.

Given the null result, cross section upper limits at the 95% C.L. are set on the HSCP production for two benchmark scenarios: direct production of $\widetilde{\mathrm{g}}$ pairs and supersymmetric top squark ($\tilde{\mathrm{t}}_1$) pairs. For a given mass, the cross section for $\widetilde{\mathrm{g}}$ production is expected to be much larger than that for $\tilde{\mathrm{t}}_1$ production at both the Tevatron and the LHC. Thus higher mass limits can be set for the former at both machines. However, as the mass of a produced particle increases, the ratio of the production cross section at the LHC to that at the Tevatron increases. For $\widetilde{\mathrm{g}}$ masses in the region of 350 GeV/c^2, the increase in relative cross section outweighs the difference in integrated luminosity between the current Tevatron and LHC data sets, enabling the LHC to set the most sensitive limits on the search for $\widetilde{\mathrm{g}}$.

Events with pair production of $\widetilde{\mathrm{g}}$ and $\tilde{\mathrm{t}}_1$, with mass values in the range 130-900 GeV/c^2, are generated with PYTHIA in order to compute the efficiency of our selection on these signals. The $\tilde{\mathrm{t}}_1$ and $\widetilde{\mathrm{g}}$ are treated as stable in all these samples and their hadronization is performed by PYTHIA. A parameter relevant to the $\widetilde{\mathrm{g}}$ pair production, and not to the $\tilde{\mathrm{t}}_1$ pair production, is the fraction, f, of produced $\widetilde{\mathrm{g}}$ hadronizing into a $\widetilde{\mathrm{g}}$-gluon state (R-gluonball). This fraction is an unknown parameter of the hadronization model and affects the fraction of R-hadrons that are neutral at production, which in turn affects the detection efficiency.

JHEP03(2011)024

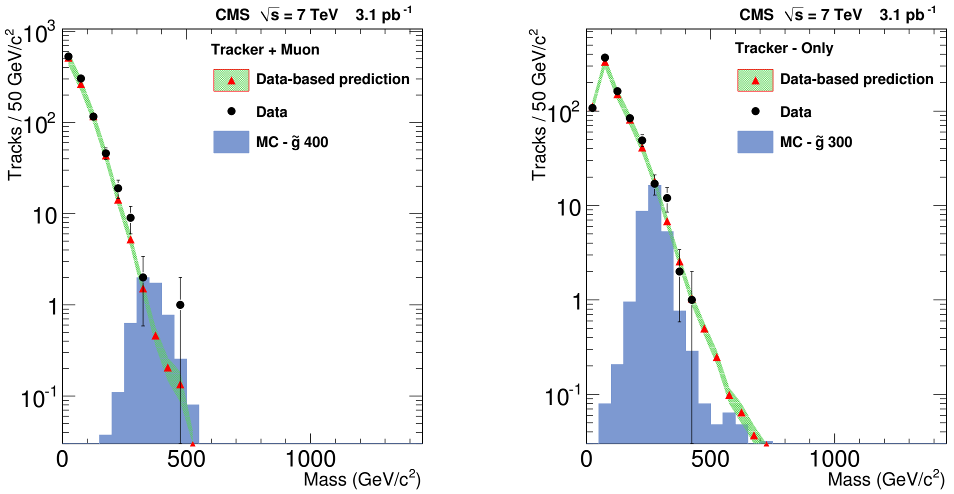

Figure 2. Mass spectrum for the loose selection defined in table 1 for the tracker-plus-muon (left) and tracker-only (right) candidates. Shown are: observed spectrum (black dots with the error bars), data-based predicted background spectrum (red triangles) with its uncertainty (green band) and the spectrum predicted by MC for a signal of pair-produced stable $\widetilde{g}$ with a mass of 400 (left) and 300 (right) GeV/c^2 (blue histogram).

LOOSE	**Mu**	**Tk**
ϵ_I	3.2×10^{-2}	1.0×10^{-2}
$I_{as}^{\min}$	0.049 - 0.162	0.007 - 0.278
ϵ_{p_T}	1.0×10^{-1}	3.2×10^{-2}
$p_T^{\min}$ (GeV/c)	34 - 36	59 - 62
Expected	$281 \pm 2(stat.) \pm 49(syst.)$	$426 \pm 1(stat.) \pm 62(syst.)$
Observed	307	452
TIGHT	**Mu**	**Tk**
ϵ_I	1.0×10^{-4}	1.0×10^{-4}
$I_{as}^{\min}$	0.184 - 0.782	0.186 - 0.784
ϵ_{p_T}	1.0×10^{-3}	3.2×10^{-4}
$p_T^{\min}$ (GeV/c)	115 - 118	154 - 210
Expected	$0.025 \pm 0.002(stat.) \pm 0.004(syst.)$	$0.074 \pm 0.002(stat.) \pm 0.011(syst.)$
Observed	0	0

Table 1. Selections used in the analysis and results of the search. The tracker-plus-muon and tracker-only selections are labeled as “Mu” and “Tk”, respectively. As explained in the text, the actual I_{as} (p_{T}) thresholds are determined in the various subsamples by the requirement of a constant efficiency for candidate selection, ϵ_I (ϵ_{p_T}). These thresholds, indicated by $I_{as}^{\min}$ ($p_T^{\min}$), are therefore reported as a range of values. Expected and observed number of candidates in the signal region are reported in the “Expected” and “Observed” rows, respectively. Top: loose selection. Bottom: tight selection.

JHEP03(2011)024

In this study, results are obtained for two different values of f, 0.1 and 0.5, to show the effect of the hadronization model uncertainty on the sensitivity of the search. The interactions of the HSCPs with the CMS apparatus and the detector response are simulated in detail with the GEANT4 v9.2 [24, 25] toolkit. The R-hadron strong interactions with matter are modeled as in ref. [26, 27]. This model, like a number of others [15, 28–30], assumes that the probability of an interaction between the heavy parton and a quark in the target nucleon is low since the cross section varies with the inverse square of the parton mass according to perturbative QCD. The adopted model chooses a pragmatic approach based on analogy with observed low energy hadron scattering. However, given the very large uncertainties on the dynamics underlying R-hadron interactions, an extremely pessimistic scenario of complete charge suppression, where each nuclear interaction suffered by the R-hadron causes it to become neutral, is also considered. The tracker-only selection is expected to have sensitivity even in such a scenario.

The total signal efficiency is reported in table 2 for some combinations of models and selections. Relatively small differences are found between the tracker-plus-muon and tracker-only selection except in the charge suppression scenario, where the tracker-plus-muon selection is completely inefficient.

This analysis is found to be complementary to the search for long-lived stopped particles presented in [17]. Indeed, for the case of $\widetilde{\mathrm{g}}$ with $f = 0.1$ and mass values below $500\,\mathrm{GeV}/c^2$, the fraction of HSCPs that have $\beta < 0.4$ and pass the final selection is less than 0.5%. Therefore the two analyses explore different ranges of produced particle velocities with no overlap.

The main sources of systematic uncertainty affecting the results presented in the following are summarized in table 3. The uncertainty on the signal selection efficiency is estimated to be 15% for all considered combinations of models and selections. The main source of this uncertainty is an assumed 10% uncertainty on the jet energy scale [31], which affects both the jet and E_T^{miss} trigger efficiency by about 10%. In a more recent study [32], the estimate of the uncertainty on the jet energy scale has been reduced by a factor of two. However, in this analysis we have conservatively chosen to retain the earlier estimate of 10%. The uncertainty on the muon trigger efficiency and the imperfect simulation of the synchronization of the muon trigger and readout electronics are studied with data and MC and are found to be the second most important source of systematic uncertainty. The total uncertainty on the trigger efficiency is 12%. The uncertainty on the offline muon track reconstruction efficiency [33], offline track reconstruction efficiency in the inner tracker [34], track momentum scale [35] and ionization energy loss scale [23] is also found to yield no more than 5% uncertainty on the overall signal selection efficiency. The uncertainty on the absolute value of the integrated luminosity is estimated to be 11% [36].

The upper limit on the cross section is computed at 95% C.L. using a Bayesian method with a flat signal prior and a log-normal prior used for integration over the nuisance parameters [19, 20, 22]. In order to obtain a conservative upper limit we set the expected background to zero. The tracker-plus-muon selection provides better limits than the tracker-only for all scenarios but the one with complete charge suppression. For each considered scenario, the cross section upper limit obtained with the most sensitive selection is reported

gluino mass (GeV/c^2)	200	300	400	500	600	900
Theoretical cross section (pb)	606	57.2	8.98	1.87	0.470	0.0130
Mu; f=0.1						
Total efficiency (%)	7.17	10.4	13.1	15.1	14.5	9.18
Expected 95% C.L. limit (pb)	15.1	10.4	8.25	7.16	7.47	11.8
Observed 95% C.L. limit (pb)	14.5	9.98	7.92	6.88	7.17	11.3
Mu; f=0.5;						
Total efficiency (%)	3.84	5.46	7.03	8.23	8.10	4.98
Expected 95% C.L. limit (pb)	28.2	19.8	15.4	13.1	13.3	21.7
Observed 95% C.L. limit (pb)	27.1	19.0	14.8	12.6	12.8	20.9
Tk; f=0.1; ch. suppr.						
Total efficiency (%)	0.59	2.44	4.16	6.39	8.60	7.66
Expected 95% C.L. limit (pb)	188	45.5	26.7	17.4	12.9	14.5
Observed 95% C.L. limit (pb)	176	42.6	25.0	16.2	12.1	13.6
stop mass (GeV/c^2)	130	200	300	500	800	
Theoretical cross section (pb)	120	13.0	1.31	0.0480	0.00110	
Mu;						
Total efficiency (%)	2.99	9.50	14.7	19.6	14.0	
Expected 95% C.L. limit (pb)	36.1	11.4	7.35	5.52	7.71	
Observed 95% C.L. limit (pb)	34.7	10.9	7.06	5.30	7.39	
Tk; ch. suppr.						
Total efficiency (%)	0.02	1.19	3.55	7.27	7.68	
Expected 95% C.L. limit (pb)	5540	93.2	31.3	15.3	14.5	
Observed 95% C.L. limit (pb)	5180	87.2	29.2	14.3	13.5	

Table 2. Total signal selection efficiency and cross section upper limits for different combinations of models and selections: pair production of supersymmetric stop and gluinos; tracker-plus-muon (Mu) and tracker-only (Tk) selections; different fractions, f, of R-gluonball states produced after hadronization and charge suppression (ch. suppr.) scenario.

Source of Systematic Error	Relative Uncertainty (%)
Theoretical cross section	10 - 25
Integrated luminosity	11
Trigger efficiency	12
Muon reconstruction efficiency	5
Track reconstruction efficiency	< 5
Momentum scale	< 5
Ionization energy loss scale	< 3
Total uncertainty on signal acceptance	15

Table 3. Sources of systematic errors and corresponding relative uncertainties.

in table 2 and figure 3, along with the theoretical predictions for $\widetilde{g}$ and $\tilde{t}_1$ pair production computed at next-to-leading order (NLO) + next-to-leading log (NLL) [37–40] using the PROSPINO v2 program [41]. The $\widetilde{g}$ theoretical predictions refer to the case where the squarks and gluino are degenerate in mass. In the heavy squark limit these cross sections are about 10% higher. For the case of $\tilde{t}_1$, beyond LO, the cross section does not only depend on the $\tilde{t}_1$ mass, but also, though to a much lesser extent [42], on the $\widetilde{g}$ mass, the average mass of the first and second generation squarks and the stop mixing angle. For this reason, the $\tilde{t}_1$ theoretical predictions reported in table 2 and figure 3 refer to the SPS1a' benchmark scenario [43]. All systematic uncertainties discussed above are included in the cross section upper limits reported in table 2 and figure 3. From the intersection of the cross section limit curve and the lower edge of the theoretical cross section band we set a 95% C.L. lower limit of 398 (357) GeV/c^2 on the mass of pair-produced $\widetilde{g}$ with $f = 0.1(0.5)$, using the tracker-plus-muon selection. The analogous limit on the $\tilde{t}_1$ mass is 202 GeV/c^2. In the charge suppression scenario we set, with the tracker-only selection, a 95% C.L. $\widetilde{g}$ mass limit of 311 GeV/c^2 for $f = 0.1$.

5 Conclusions

In summary, the CMS detector has been used to identify highly ionizing, high-p_T particles and measure their masses. Two searches have been conducted: a very inclusive and model independent one that uses highly-ionizing tracks reconstructed in the inner tracker detector, and another requiring also that these tracks be identified in the CMS muon system. In each case, the observed distribution of the candidate masses is consistent with the expected background. We have set lower limits on masses of stable strongly interacting supersymmetric particles. For the case of $\widetilde{g}$ with $f = 0.1$ and $\tilde{t}_1$, a lower mass limit of 398 and 202 GeV/c^2, respectively, is set at the 95% C.L. with the analysis that uses muon identification. In a pessimistic scenario of complete charge suppression the above $\widetilde{g}$ mass limit is reduced to 311 GeV/c^2 and is obtained with the tracker-only selection. The limits presented here on stable $\widetilde{g}$ are the most restrictive to date.

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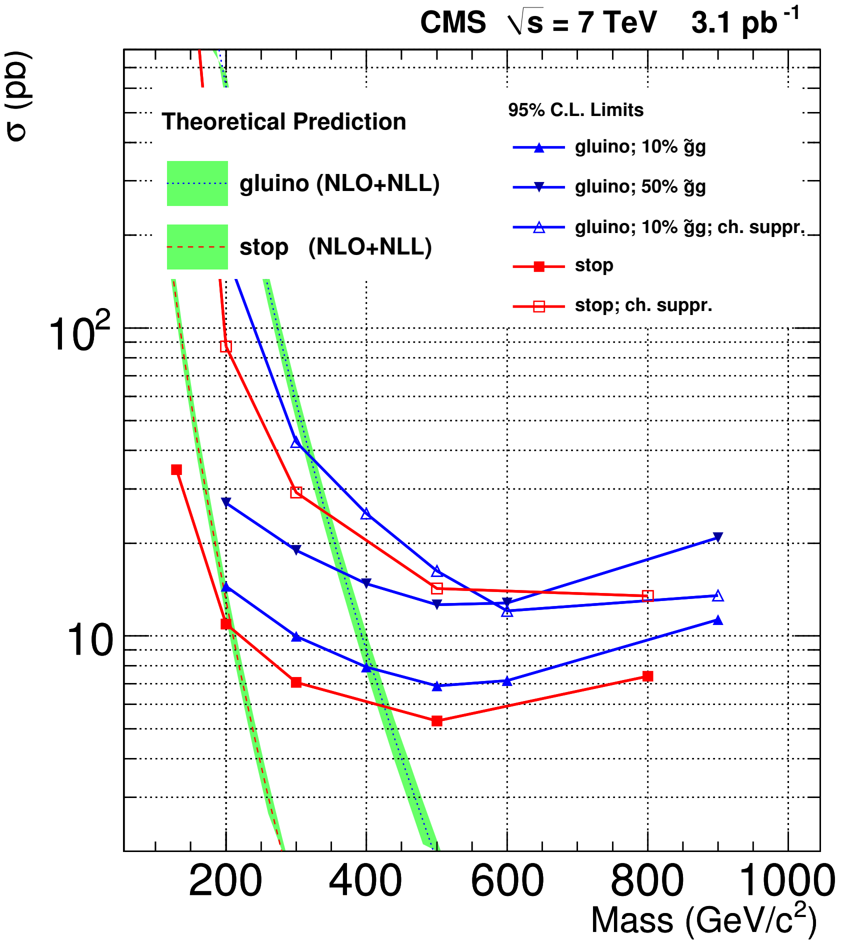

Figure 3. Predicted theoretical cross section and observed 95% C.L. upper limits on the cross section for the different combinations of models and scenarios considered: pair production of supersymmetric stop and gluinos; different fractions, f, of R-gluonball states produced after hadronization and charge suppression ("ch. suppr.") scenarios. Only the results obtained with the most sensitive selection are reported: tracker-only for the charge suppression scenarios and tracker-plus-muon for all other cases. The bands represent the theoretical uncertainties on the cross section values.

(India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer[1], S. Hänsel, C. Hartl, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, G. Kasieczka, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

L. Benucci, L. Ceard, K. Cerny, E.A. De Wolf, X. Janssen, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

V. Adler, S. Beauceron, F. Blekman, S. Blyweert, J. D'Hondt, O. Devroede, R. Gonzalez Suarez, A. Kalogeropoulos, J. Maes, M. Maes, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wickens

Ghent University, Ghent, Belgium

S. Costantini, M. Grunewald, B. Klein, A. Marinov, J. Mccartin, D. Ryckbosch, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

S. Basegmez, G. Bruno, J. Caudron, J. De Favereau De Jeneret, C. Delaere, P. Demin, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, S. Ovyn, D. Pagano, A. Pin, K. Piotrzkowski, L. Quertenmont, N. Schul

Université de Mons, Mons, Belgium

N. Beliy, T. Caebergs, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W. Carvalho, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
F.A. Dias, M.A.F. Dias, T.R. Fernandez Perez Tomei, E. M. Gregores[2], F. Marinho, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
N. Darmenov[1], L. Dimitrov, V. Genchev[1], P. Iaydjiev[1], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, I. Vankov

University of Sofia, Sofia, Bulgaria
M. Dyulendarova, R. Hadjiiska, V. Kozhuharov, L. Litov, E. Marinova, M. Mateev, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, J. Wang, J. Wang, X. Wang, Z. Wang, M. Xu, M. Yang, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China
Y. Ban, S. Guo, W. Li, Y. Mao, S.J. Qian, H. Teng, L. Zhang, B. Zhu

Universidad de Los Andes, Bogota, Colombia
A. Cabrera, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, K. Lelas, R. Plestina[3], D. Polic, I. Puljak

University of Split, Split, Croatia
Z. Antunovic, M. Dzelalija

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, S. Morovic

University of Cyprus, Nicosia, Cyprus
A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[4], M.A. Mahmoud[5]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
A. Hektor, M. Kadastik, K. Kannike, M. Müntel, M. Raidal, L. Rebane

Department of Physics, University of Helsinki, Helsinki, Finland
V. Azzolini, P. Eerola

Helsinki Institute of Physics, Helsinki, Finland
S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, J. Klem, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
K. Banzuzi, A. Korpela, T. Tuuva

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France

D. Sillou

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, L. Bianchini, M. Bluj[6], C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, B. Wyslouch[7], A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram[8], J. Andrea, A. Besson, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte[8], F. Drouhin[8], C. Ferro, J.-C. Fontaine[8], D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim[8], A.-C. Le Bihan, Y. Mikami, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France

F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

C. Baty, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, A. Falkiewicz, J. Fay, S. Gascon, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, H. Xiao

E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia

V. Roinishvili

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

G. Anagnostou, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, N. Mohr, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, M. Weber, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Ata, W. Bender, M. Erdmann, J. Frangenheim, T. Hebbeker, A. Hinzmann, K. Hoepfner, C. Hof, T. Klimkovich, D. Klingebiel, P. Kreuzer, D. Lanske[†], C. Magass, G. Masetti, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Bontenackels, M. Davids, M. Duda, G. Flügge, H. Geenen, M. Giffels, W. Haj Ahmad, D. Heydhausen, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, M. Thomas, D. Tornier, M.H. Zoeller

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz[9], K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, I. Glushkov, J. Hauk, H. Jung, M. Kasemann, I. Katkov, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann[9], R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, A. Parenti, A. Raspereza, A. Raval, R. Schmidt[9], T. Schoerner-Sadenius, N. Sen, M. Stein, J. Tomaszewska, D. Volyanskyy, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

C. Autermann, S. Bobrovskyi, J. Draeger, H. Enderle, U. Gebbert, K. Kaschube, G. Kaussen, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, M. Schröder, T. Schum, J. Schwandt, A.K. Srivastava, H. Stadie, G. Steinbrück, J. Thomsen, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Bauer, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, S.M. Heindl, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, D. Piparo, G. Quast, K. Rabbertz, F. Ratnikov, M. Renz, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, M. Zeise, V. Zhukov[10], E.B. Ziebarth

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Petrakou

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou[1]

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

A. Aranyi, G. Bencze, L. Boldizsar, G. Debreczeni, C. Hajdu[1], D. Horvath[11], A. Kapusi, K. Krajczar[12], A. Laszlo, F. Sikler, G. Vesztergombi[12]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, N. Dhingra, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J.B. Singh, S.P. Singh

University of Delhi, Delhi, India

S. Ahuja, S. Bhattacharya, B.C. Choudhary, P. Gupta, S. Jain, S. Jain, A. Kumar, R.K. Shivpuri

Bhabha Atomic Research Centre, Mumbai, India

R.K. Choudhury, D. Dutta, S. Kailas, S.K. Kataria, A.K. Mohanty[1], L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, M. Guchait[13], A. Gurtu, M. Maity[14], D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad, N.K. Mondal

Institute for Studies in Theoretical Physics & Mathematics (IPM), Tehran, Iran

H. Arfaei, H. Bakhshiansohi, S.M. Etesami, A. Fahim, M. Hashemi, A. Jafari, M. Khakzad, A. Mohammadi, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy

M. Abbrescia[a,b], L. Barbone[a,b], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Dimitrov[a], L. Fiore[a], G. Iaselli[a,c], L. Lusito[a,b,1], G. Maggi[a,c], M. Maggi[a], N. Manna[a,b], B. Marangelli[a,b], S. My[a,c], S. Nuzzo[a,b], N. Pacifico[a,b], G.A. Pierro[a], A. Pompili[a,b], G. Pugliese[a,c], F. Romano[a,c], G. Roselli[a,b], G. Selvaggi[a,b], L. Silvestris[a], R. Trentadue[a], S. Tupputi[a,b], G. Zito[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy

G. Abbiendi[a], A.C. Benvenuti[a], D. Bonacorsi[a], S. Braibant-Giacomelli[a,b], L. Brigliadori[a], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], M. Giunta[a], S. Marcellini[a], M. Meneghelli[a,b], A. Montanari[a], F.L. Navarria[a,b], F. Odorici[a], A. Perrotta[a], F. Primavera[a], A.M. Rossi[a,b], T. Rovelli[a,b], G. Siroli[a,b], R. Travaglini[a,b]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy

S. Albergo[a,b], G. Cappello[a,b], M. Chiorboli[a,b,1], S. Costa[a,b], A. Tricomi[a,b], C. Tuve[a]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy

G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Frosali[a,b], E. Gallo[a], C. Genta[a], P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,1]

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi[15], F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy
P. Fabbricatore, R. Musenich

INFN Sezione di Milano-Biccoca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a,b], F. De Guio[a,b,1], L. Di Matteo[a,b], A. Ghezzi[a,b,1], M. Malberti[a,b], S. Malvezzi[a], A. Martelli[a,b], A. Massironi[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], S. Sala[a], T. Tabarelli de Fatis[a,b], V. Tancini[a,b]

INFN Sezione di Napoli [a], Università di Napoli "Federico II" [b], Napoli, Italy
S. Buontempo[a], C.A. Carrillo Montoya[a], A. Cimmino[a,b], A. De Cosa[a,b], M. De Gruttola[a,b], F. Fabozzi[a,16], A.O.M. Iorio[a], L. Lista[a], M. Merola[a,b], P. Noli[a,b], P. Paolucci[a]

INFN Sezione di Padova [a], Università di Padova [b], Università di Trento (Trento) [c], Padova, Italy
P. Azzi[a], N. Bacchetta[a], P. Bellan[a,b], D. Bisello[a,b], A. Branca[a], R. Carlin[a,b], E. Conti[a], M. De Mattia[a,b], T. Dorigo[a], F. Fanzago[a], F. Gasparini[a,b], P. Giubilato[a,b], F. Gonella[a], A. Gresele[a,c], S. Lacaprara[a,17], I. Lazzizzera[a,c], M. Margoni[a,b], M. Mazzucato[a], A.T. Meneguzzo[a,b], M. Nespolo[a], M. Pegoraro[a], L. Perrozzi[a,1], N. Pozzobon[a,b], P. Ronchese[a,b], E. Torassa[a], M. Tosi[a,b], A. Triossi[a], S. Vanini[a,b], S. Ventura[a], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
P. Baesso[a,b], U. Berzano[a], C. Riccardi[a,b], P. Torre[a,b], P. Vitulo[a,b], C. Viviani[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], B. Caponeri[a,b], L. Fanò[a,b], P. Lariccia[a,b], A. Lucaroni[a,b,1], G. Mantovani[a,b], M. Menichelli[a], A. Nappi[a,b], A. Santocchia[a,b], L. Servoli[a], S. Taroni[a,b], M. Valdata[a,b], R. Volpe[a,b,1]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
P. Azzurri[a,c], G. Bagliesi[a], J. Bernardini[a,b], T. Boccali[a,1], G. Broccolo[a,c], R. Castaldi[a], R.T. D'Agnolo[a,c], R. Dell'Orso[a], F. Fiori[a,b], L. Foà[a,c], A. Giassi[a], A. Kraan[a], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a], A. Messineo[a,b], F. Palla[a], F. Palmonari[a], S. Sarkar[a,c], G. Segneri[a], A.T. Serban[a], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b,1], A. Venturi[a,1], P.G. Verdini[a]

INFN Sezione di Roma [a], Università di Roma "La Sapienza" [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], D. Franci[a,b], M. Grassi[a], E. Longo[a,b], G. Organtini[a,b], A. Palma[a,b], F. Pandolfi[a,b,1], R. Paramatti[a], S. Rahatlou[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Università del Piemonte Orientale (Novara) [c], Torino, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], C. Biino[a], C. Botta[a,b,1], N. Cartiglia[a], R. Castello[a,b], M. Costa[a,b], N. Demaria[a], A. Graziano[a,b,1], C. Mariotti[a], M. Marone[a,b], S. Maselli[a], E. Migliore[a,b], G. Mila[a,b], V. Monaco[a,b], M. Musich[a,b],

M.M. Obertino[a,c], N. Pastrone[a], M. Pelliccioni[a,b,1], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], D. Trocino[a,b], A. Vilela Pereira[a,b,1]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
F. Ambroglini[a,b], S. Belforte[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], D. Montanino[a,b], A. Penzo[a]

Kangwon National University, Chunchon, Korea
S.G. Heo

Kyungpook National University, Daegu, Korea
S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, D. Son, D.C. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
Zero Kim, J.Y. Kim, S. Song

Korea University, Seoul, Korea
S. Choi, B. Hong, M. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, H.B. Rhee, E. Seo, S. Shin, K.S. Sim

University of Seoul, Seoul, Korea
M. Choi, S. Kang, H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Choi, Y.K. Choi, J. Goh, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania
M.J. Bilinskas, I. Grigelionis, M. Janulis, D. Martisiute, P. Petrov, T. Sabonis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla Valdez, E. De La Cruz Burelo, R. Lopez-Fernandez, A. Sánchez Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand
P. Allfrey, D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler, R. Doesburg, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, I. Ahmed, M.I. Asghar, H.R. Hoorani, W.A. Khan, T. Khurshid, S. Qazi

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland

T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

N. Almeida, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, P. Martins, P. Musella, A. Nayak, P.Q. Ribeiro, J. Seixas, P. Silva, J. Varela[1], H.K. Wöhri

Joint Institute for Nuclear Research, Dubna, Russia

I. Belotelov, P. Bunin, M. Finger, M. Finger Jr., I. Golutvin, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia

N. Bondar, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, V. Kaftanov[†], M. Kossov[1], A. Krokhotin, N. Lychkovskaya, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

E. Boos, M. Dubinin[18], L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, S. Bitioukov, V. Grishin[1], V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, S. Slabospitsky, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic[19], M. Djordjevic, D. Krpic[19], J. Milosevic

JHEP03(2011)024

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, M. Chamizo Llatas, S.H. Chuang, J. Duarte Campderros, M. Felcini[20], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez[21], T. Rodrigo, A. Ruiz Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, A.J. Bell[22], D. Benedetti, C. Bernet[3], W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, H. Breuker, G. Brona, K. Bunkowski, T. Camporesi, E. Cano, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, F. Duarte Ramos, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, S. Gennai, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, P. Govoni, S. Gowdy, L. Guiducci, M. Hansen, J. Harvey, J. Hegeman, B. Hegner, C. Henderson, G. Hesketh, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot, E. Karavakis, P. Lecoq, C. Leonidopoulos, C. Lourenço, A. Macpherson, T. Mäki, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold[1], M. Nguyen, T. Orimoto, L. Orsini, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, G. Polese, A. Racz, G. Rolandi[23], T. Rommerskirchen, C. Rovelli[24], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, M. Simon, P. Sphicas[25], D. Spiga, M. Spiropulu[18], F. Stöckli, M. Stoye, P. Tropea, A. Tsirou, A. Tsyganov, G.I. Veres[12], P. Vichoudis, M. Voutilainen, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille[26], A. Starodumov[27]

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

P. Bortignon, L. Caminada[28], Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, A. Hervé, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica[28], P. Martinez Ruiz del Arbol, P. Meridiani, P. Milenovic[29], F. Moortgat, P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, B. Stieger, L. Tauscher†, A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny[20], M. Weber, L. Wehrli, J. Weng

Universität Zürich, Zurich, Switzerland

E. Aguiló, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, C. Regenfus, P. Robmann, A. Schmidt, H. Snoek, L. Wilke

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.H. Chen, W.T. Chen, S. Dutta, A. Go, C.M. Kuo, S.W. Li, W. Lin, M.H. Liu, Z.K. Liu, Y.J. Lu, J.H. Wu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, J.G. Shiu, Y.M. Tzeng, M. Wang

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci[30], S. Cerci[31], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, A. Kayis Topaksu, A. Nart, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut[32], B. Tali, H. Topakli[30], D. Uzun, L.N. Vergili, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey

M. Deliomeroglu, D. Demir[33], E. Gülmez, A. Halu, B. Isildak, M. Kaya[34], O. Kaya[34], S. Ozkorucuklu[35], N. Sonmez[36]

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

P. Bell, F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, M. Hansen, D. Hartley, G.P. Heath, H.F. Heath, B. Huckvale, J. Jackson, L. Kreczko, S. Metson, D.M. Newbold[37], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, S. Ward

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso, K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, G. Davies, M. Della Negra, J. Fulcher, D. Futyan, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, R. Nandi, J. Nash, A. Nikitenko[27], A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi[38], D.M. Raymond, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, D. Wardrope, T. Whyntie

Brunel University, Uxbridge, United Kingdom

M. Barrett, M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, W. Martin, I.D. Reid, L. Teodorescu

Baylor University, Waco, USA

K. Hatakeyama

Boston University, Boston, USA

T. Bose, E. Carrera Jarrin, A. Clough, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA

A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Narain, D. Nguyen, M. Segala, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA

M.A. Borgia, R. Breedon, M. Calderon De La Barca Sanchez, D. Cebra, S. Chauhan, M. Chertok, J. Conway, P.T. Cox, J. Dolen, R. Erbacher, E. Friis, W. Ko, A. Kopecky, R. Lander, H. Liu, S. Maruyama, T. Miceli, M. Nikolic, D. Pellett, J. Robles, S. Salur, T. Schwarz, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, C. Veelken

University of California, Los Angeles, Los Angeles, USA

V. Andreev, K. Arisaka, D. Cline, R. Cousins, A. Deisher, J. Duris, S. Erhan, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev

University of California, Riverside, Riverside, USA

J. Babb, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, A. Luthra, H. Nguyen, G. Pasztor[39], A. Satpathy, B.C. Shen[†], R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, E. Dusinberre, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, B. Mangano, J. Muelmenstaedt, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma[1], S. Simon, Y. Tu, A. Vartak, F. Würthwein, A. Yagil

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette,

N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant

California Institute of Technology, Pasadena, USA

A. Bornheim, J. Bunn, Y. Chen, M. Gataullin, D. Kcira, V. Litvine, Y. Ma, A. Mott, H.B. Newman, C. Rogan, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, N. Terentyev, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

J.P. Cumalat, M.E. Dinardo, B.R. Drell, C.J. Edelmaier, W.T. Ford, B. Heyburn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

Cornell University, Ithaca, USA

L. Agostino, J. Alexander, A. Chatterjee, S. Das, N. Eggert, L.J. Fields, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, V. Kuznetsov, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, D. Riley, A. Ryd, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

A. Biselli, G. Cirino, D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, F. Borcherding, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, M. Demarteau, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, K. Gunthoti, O. Gutsche, A. Hahn, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, E. James, H. Jensen, M. Johnson, U. Joshi, R. Khatiwada, B. Kilminster, B. Klima, K. Kousouris, S. Kunori, S. Kwan, P. Limon, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. McCauley, T. Miao, K. Mishra, S. Mrenna, Y. Musienko[40], C. Newman-Holmes, V. O'Dell, S. Popescu[41], R. Pordes, O. Prokofyev, N. Saoulidou, E. Sexton-Kennedy, S. Sharma, A. Soha, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, S. Goldberg, B. Kim, S. Klimenko, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, K. Matchev, G. Mitselmakher, L. Muniz, Y. Pakhotin, C. Prescott, R. Remington, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, D. Wang, J. Yelton, M. Zakaria

JHEP03(2011)024

Florida International University, Miami, USA
C. Ceron, V. Gaultney, L. Kramer, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
T. Adams, A. Askew, D. Bandurin, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, S. Sekmen, V. Veeraraghavan

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, B. Dorney, S. Guragain, M. Hohlmann, H. Kalakhety, R. Ralich, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, E.J. Garcia-Solis, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, C. O'Brien, C. Silvestre, A. Smoron, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki, K. Cankocak[42], W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA
B.A. Barnett, B. Blumenfeld, A. Bonato, C. Eskew, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, O. Grachov, M. Murray, D. Noonan, V. Radicci, S. Sanders, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA
T. Bolton, I. Chakaberia, A. Ivanov, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze, Z. Wan

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA
A. Baden, M. Boutemeur, S.C. Eno, D. Ferencek, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, Y. Lu, A.C. Mignerey, K. Rossato, P. Rumerio, F. Santanastasio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA
B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, P. Everaerts, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, P. Harris, Y. Kim, M. Klute, Y.-J. Lee, W. Li, C. Loizides, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, K. Sumorok, K. Sung, E.A. Wenger, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA
P. Cole, S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, P.R. Dudero, G. Franzoni, J. Haupt, K. Klapoetke, Y. Kubota, J. Mans, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky

University of Mississippi, University, USA
L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, T. Kelly, I. Kravchenko, J. Lazo-Flores, C. Lundstedt, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
U. Baur, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, O. Boeriu, M. Chasco, K. Kaadze, S. Reucroft, J. Swain, D. Wood, J. Zhang

Northwestern University, Evanston, USA
A. Anastassov, A. Kubik, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA
L. Antonelli, D. Berry, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, T. Kolberg, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, J. Warchol, M. Wayne, J. Ziegler

The Ohio State University, Columbus, USA
B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, G. Williams

Princeton University, Princeton, USA
N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, A. Hunt, J. Jones, E. Laird, D. Lopes Pegna, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA
J.G. Acosta, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, USA
E. Alagoz, V.E. Barnes, G. Bolla, L. Borrello, D. Bortoletto, A. Everett, A.F. Garfinkel, Z. Gecse, L. Gutay, Z. Hu, M. Jones, O. Koybasi, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, K. Potamianos, I. Shipsey, D. Silvers, A. Svyatkovskiy, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA
P. Jindal, N. Parashar

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Rice University, Houston, USA

C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, J.H. Liu, J. Morales, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, H. Flacher, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, D. Orbaker, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA

A. Bhatti, L. Demortier, K. Goulianos, G. Lungu, C. Mesropian, M. Yan

Rutgers, the State University of New Jersey, Piscataway, USA

O. Atramentov, A. Barker, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, R. Patel, A. Richards, K. Rose, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA

J. Asaadi, R. Eusebi, J. Gilmore, A. Gurrola, T. Kamon, V. Khotilovich, R. Montalvo, C.N. Nguyen, I. Osipenkov, J. Pivarski, A. Safonov, S. Sengupta, A. Tatarinov, D. Toback, M. Weinberger

Texas Tech University, Lubbock, USA

N. Akchurin, C. Bardak, J. Damgov, C. Jeong, K. Kovitanggoon, S.W. Lee, P. Mane, Y. Roh, A. Sill, I. Volobouev, R. Wigmans, E. Yazgan

Vanderbilt University, Nashville, USA

E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, M. Balazs, S. Boutle, M. Buehler, S. Conetti, B. Cox, B. Francis, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, R. Yohay

Wayne State University, Detroit, USA

S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

University of Wisconsin, Madison, USA

M. Anderson, M. Bachtis, J.N. Bellinger, D. Carlsmith, S. Dasu, J. Efron, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton[1], M. Herndon, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, D. Lomidze, R. Loveless, A. Mohapatra, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

†: Deceased
1; Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
2: Also at Universidade Federal do ABC, Santo Andre, Brazil
3: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
4: Also at Suez Canal University, Suez, Egypt
5: Also at Fayoum University, El-Fayoum, Egypt
6: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
7: Also at Massachusetts Institute of Technology, Cambridge, USA
8: Also at Université de Haute-Alsace, Mulhouse, France
9: Also at Brandenburg University of Technology, Cottbus, Germany
10: Also at Moscow State University, Moscow, Russia
11: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
12: Also at Eötvös Loránd University, Budapest, Hungary
13: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
14: Also at University of Visva-Bharati, Santiniketan, India
15: Also at Facoltà Ingegneria Università di Roma ”La Sapienza”, Roma, Italy
16: Also at Università della Basilicata, Potenza, Italy
17: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
18: Also at California Institute of Technology, Pasadena, USA
19: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
20: Also at University of California, Los Angeles, Los Angeles, USA
21: Also at University of Florida, Gainesville, USA
22: Also at Université de Genève, Geneva, Switzerland
23: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
24: Also at INFN Sezione di Roma; Università di Roma ”La Sapienza”, Roma, Italy
25: Also at University of Athens, Athens, Greece
26: Also at The University of Kansas, Lawrence, USA
27: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
28: Also at Paul Scherrer Institut, Villigen, Switzerland
29: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
30: Also at Gaziosmanpasa University, Tokat, Turkey
31: Also at Adiyaman University, Adiyaman, Turkey
32: Also at Mersin University, Mersin, Turkey
33: Also at Izmir Institute of Technology, Izmir, Turkey
34: Also at Kafkas University, Kars, Turkey
35: Also at Suleyman Demirel University, Isparta, Turkey
36: Also at Ege University, Izmir, Turkey
37: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
38: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
39: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
40: Also at Institute for Nuclear Research, Moscow, Russia
41: Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
42: Also at Istanbul Technical University, Istanbul, Turkey